Superconducting Strand Quench Development Tests

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INTRODUCTION

The Fermilab Technical Division is engaged in the design, production, and testing of devices for the HINS R&D proton LINAC [1]. For the CH section of the machine, production of superconducting focusing solenoids is approaching completion, and the tested cold masses are being assembled into cryostats. Cryostatted lens assemblies will all be cold tested in MTF to verify that performance meets requirements, and to determine warm and cold solenoid axis and dipole angle alignment for installation into the beam line. As these devices will be installed in a beam line and operated with a power and quench protection system (QPS) designed by the Fermilab Accelerator Division, some coordination and certification of the required instrumentation was necessary. In R&D magnets, it is standard practice to protect the superconducting (SC) leads using dedicated voltage tap segments that span the entire length of each SC lead. It was recognized that a great deal of added labor, cost, and complexity would be needed to provide this special SC lead protection for production solenoids and cryostatted lenses, so it became important to establish whether this was really necessary.

PROTOTYPE CRYOSTAT

Prior to the start of cryostat production, a prototype focusing solenoid in a helium vessel was assembled into a prototype version, which was subsequently tested. The primary test goals were to check the performance, establish the alignment technique, and give an opportunity to feed back on the design of both the cryostat and operational systems [2]. This device, labeled HCH-P-001, has been useful for a variety of system and performance tests which have taken place over a period of one year. The prototype Type-1 assembly (without steering dipole coils) differed slightly from the production design: instead of HTS power leads (which were not yet available), the cryostat has one pair of 300 A vapor-cooled copper leads; also, no LN2 control valve was installed for shield flow control.

The first prototype focusing solenoid, HINS_CH_SOL_01, was used to build the prototype cryostat lens. A previously tested R&D magnet [3], it had been instrumented with more voltage taps than would be used for production magnets: in particular, the Main Coil (MC) included a center tap to allow "half coil" segments for effective quench detection. The electrical configuration for HCH-P-001 is illustrated in Figure 1. Note that the positive Half coil (H^+) extends from the positive superconducting lead (SC+) to the MC center tap; the negative Half coil (H-) starts from the MC center tap and extends to the negative lead (SC-), and thus it includes both BCs. (The BCs have small inductance, so the two Half coils are still closely balanced for quench detection). A length of 0.8mm superconductor strand connects the positive (CU+) and negative (CU-) copper leads to the solenoid leads; the MC is wound from 0.8 mm round strand, and so SC+ is 0.8mm in diameter, while the BCs are wound from 0.6 mm round strand, and SC- is 0.6 mm in diameter. The SC lead voltage taps were located at the copper to SC strand joints, and close to the solenoid body; thus, the leads were protected by dedicated voltage taps. The splices between superconductor strands were each about 5 cm long. The exact lengths of each SC segment were not recorded during construction, but can be estimated from ongoing production assemblies: L1(CU to splice) ~ 13 mm, L2(splice to coil) ~ 20 mm; total length L1+L2 ~ 33 mm. These lengths may be used later to estimate the actual quench velocity in the strands.

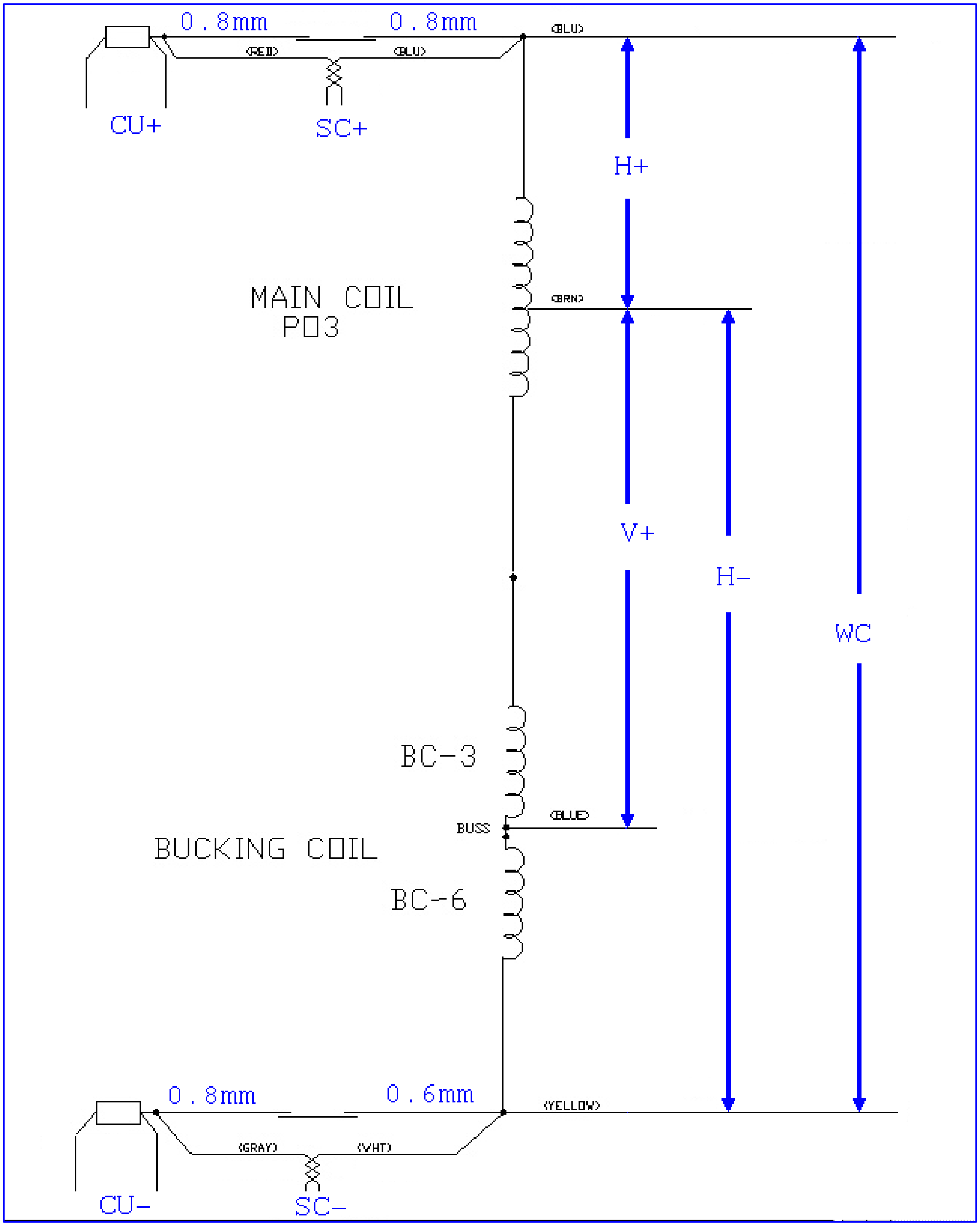

Figure 1. Electrical Schematic for HINS_CH_SOL_01-1 and HCH-P-001 showing instrumented quench characterization voltage tap segments.

METHOD

It was recognized early in quench testing of the prototype lens that inadequate helium gas flow through the copper leads resulted in quenches of the SC leads during ramping at high current. This subsequently led to the realization that SC lead quenches could be induced by reducing the flow below the minimum required level. A test plan to study quench propagation in the SC leads was developed to systematically induce quenches in positive and negative SC leads over a range of solenoid operating currents that will be possible in beam line conditions. The questions to be answered were whether quenches would develop and propagate; if so how quickly would they reach the coil and how would voltage develop in the SC lead.

The plan was performed in three separate test periods, which mapped the behavior in three different ranges of solenoid current. The first set of data was captured by the original MQPS-1 (mobile quench and power system) cart for quench detection and characterization, which was shared between Stand 3 R&D solenoid testing, and Stand 6 cryostat lens testing. For the second and third data sets, a second cart MQPS-2 was used, shortly after it had been commissioned with a dummy load. Table 1 shows the date and time for individual quench events (which identifies the quench data files), and magnet currents explored during three study periods. In each data set a point overlapping with the previous set was recorded to check consistency. The noise levels for signals recorded with MQPS-2 appear to be somewhat greater than for MQPS-1. For unknown reasons, not immediately recognized, problems developed with the half coil characterization signals during the third test period; however the SCL signals worked.

Table 1. SC Lead Quench Development Study Data Sets

POSITIVE DATE	SC LEAD TIME	QUENCH CURRENT	NEGATIVE DATE	SC LEAD TIME	QUENCH CURRENT
10/31/2008	11:13:48	235	10/29/2008	15:02:34	235
10/31/2008	11:31:33	220	10/29/2008	15:20:44	220
10/31/2008	11:49:24	200	10/29/2008	15:37:25	200
10/31/2008	12:02:26	180	10/30/2008	09:43:09	180
12/8/2008	16:30:44	180	12/8/2008	16:39:57	180
12/8/2008	16:47:47	160	12/8/2008	16:54:28	160
12/8/2008	17:00:18	140	12/8/2008	17:06:24	140
1/15/2009	09:58:34	140	1/15/2009	09:43:11	140
1/15/2009	10:22:03	120	1/15/2009	10:09:08	120
1/15/2009	10:25:30	94	1/15/2009	10:30:50	100
1/15/2009	10:43:14	100	1/15/2009	10:38:13	100
1/15/2009	11:02:51	85	1/15/2009	11:02:51	85

To prevent mishaps that might accidentally damage the device, a detailed test procedure was developed. However, the approach was straightforward: 1) adjust thresholds of the quench detection circuits to appropriate levels; 2) establish the minimum required helium vapor flow through copper leads for high current operation; 3) reset/arm the QPS and ramp (at 1 A/s) the solenoid to the target current level; 4) slowly reduce the helium flow on one of the copper leads - some manual adjustment of the copper lead threshold may be required to prevent system trip due to growing lead resistance; 5) quench – capture data automatically and review it. Following all of the SC lead quench tests, we ramped the solenoid to quench at its nominal current of 243 A to demonstrate that no degradation of the SC leads was evident.

At high current it was necessary to raise the SC lead protection threshold somewhat to allow the quench to propagate to the coil; as the current was lowered, the quench development time increased, and the SC lead voltage decreased. The quench at 94 A was the result of ramping without having raised the lead flow again after the previous (120 A) test. At 100 A we noticed the voltage development was very slow, taking longer than the 1 second of captured quench data; subsequently the quench data buffer was increased to capture 2 seconds of data before the quench (though even this was not adequate to capture the entire voltage development from quench onset).

RESULTS

We were unable to induce a quench below 85 A, even with both lead flows at zero. In this case, the positive and negative SC lead voltages were both stable at about 5 or 6 mV each. At 85 A with both flows at zero, the summed SC lead voltage was 12 mV, but the quench propagated to the coils and was detected; it is not clear which coil quenched in this case, due to the half coil signal problem during this final test period.

The current dependence of SC lead voltage development for the negative lead is shown in Figure 2, and for the positive SC lead in Figure 3. The trend for both is the same: a fast rising start that reaches a knee, followed by a slower development which accelerates with time. There is some consistent structure seen around the knee in the voltage traces. The initial rate of rise is the same for both positive and negative leads, as would be expected since both are 0.8 mm strands connected to the hot copper lead where the quench starts. The turn-over to a slower developing quench front can be explained qualitatively by the presence of the splice to magnet lead, which has extra mass in leads, solder, and wire wrap to act as stabilizer. The slow region development that follows is different in the positive and negative leads, because of the different strand diameters. It takes about 50% longer, in general, for the quench to propagate to the coil in the smaller strand; however the voltage as a function of time is about the same for both (thus, more voltage is developed in the smaller diameter lead by the time the quench is detected). The average quench propagation velocity over the (approximately) 33 mm length of strand is only 0.13 m/s for SC- (0.165 m/s for SC+) at the nominal operating current of 180 A.

The quench development in coils that result from SCL quenches is shown in Figure 4 for the Negative SCL quench, and Figure 5 for the Positive SCL quench, at currents of 140 to 235 A. The SC leads emerge from the inner layer winding of both the Main and Bucking Coils, therefore these quenches develop in the high field region of each. Being at lower field, the BC quenches develop more slowly.

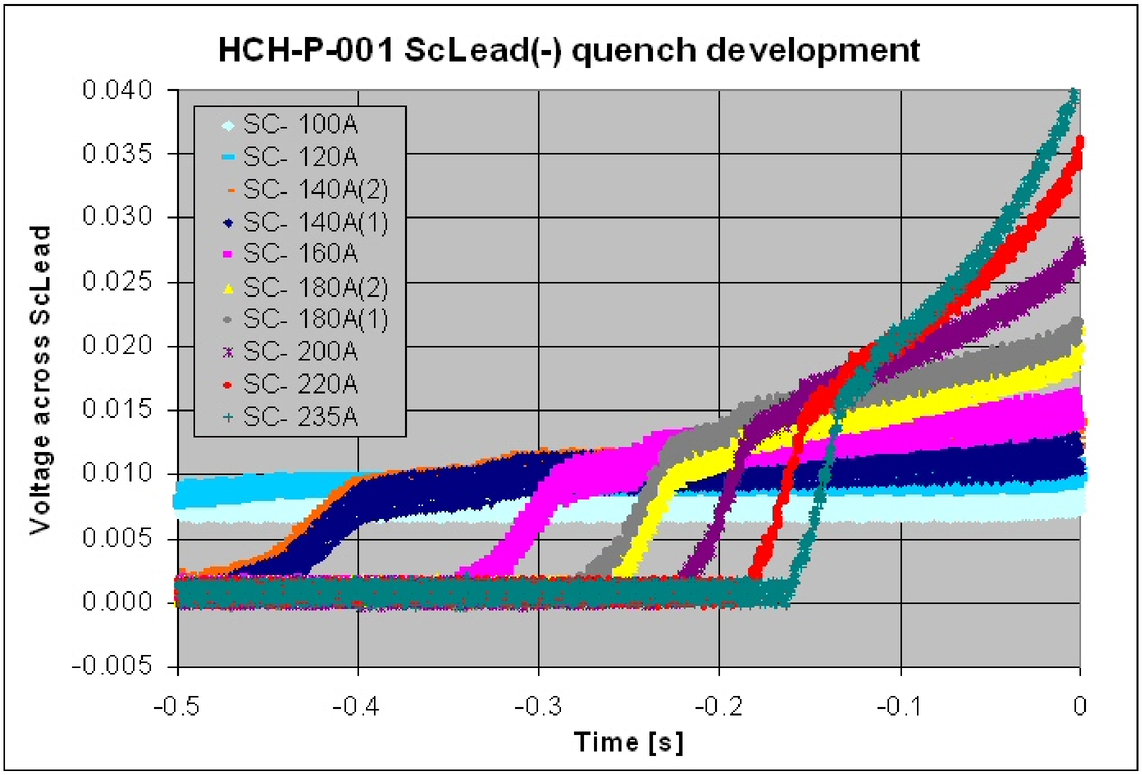

Figure 2. Negative SC lead voltage development as a function of solenoid current.

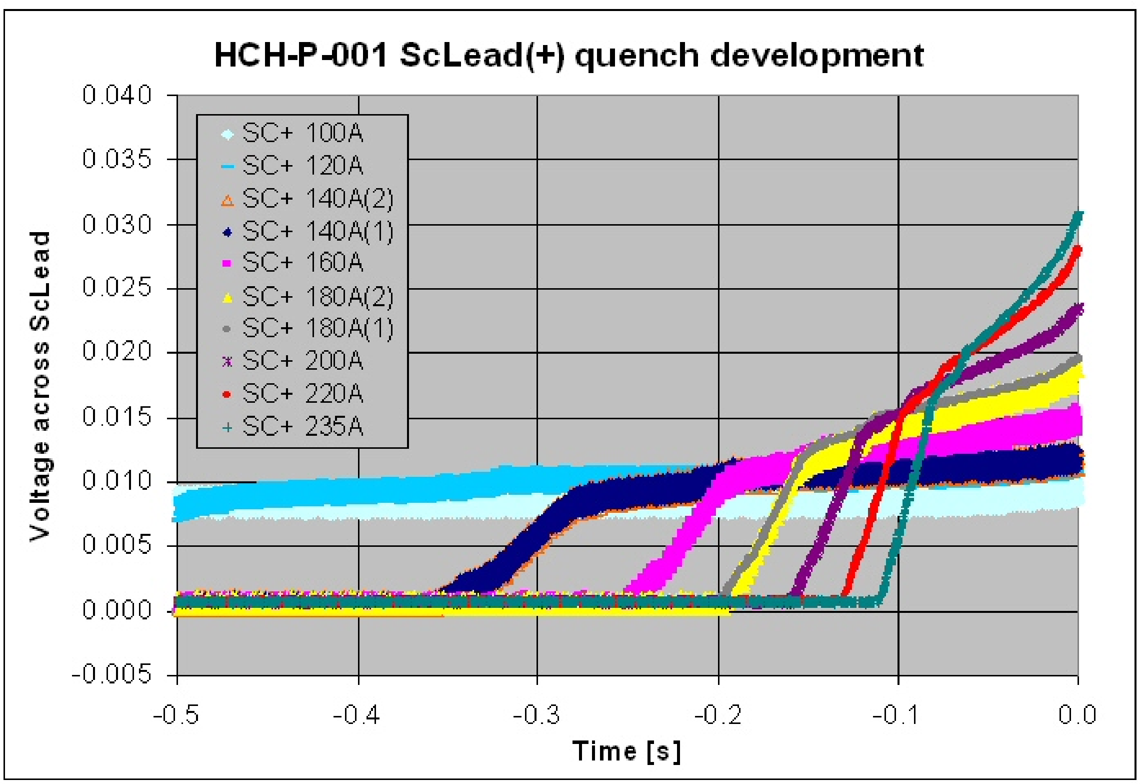

Figure 3. Positive SC lead voltage development as a function of solenoid current.

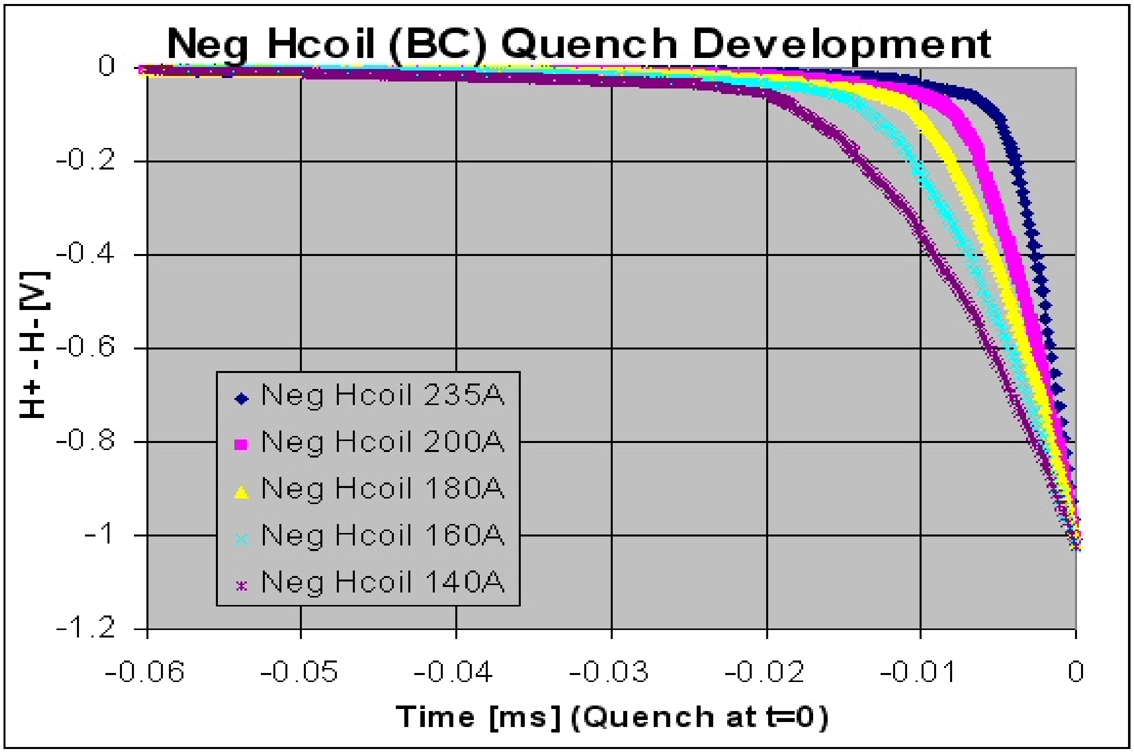

Figure 4. Half Coil (Bucking Coil) quench development following SC- Lead quench.

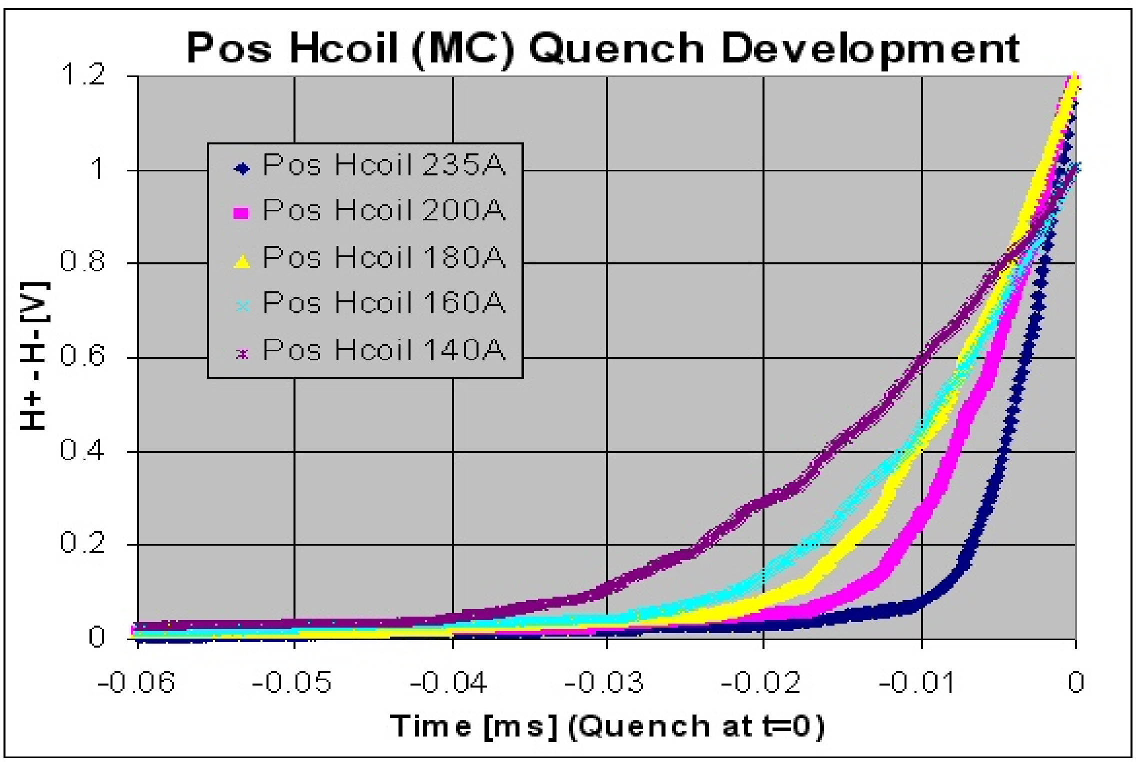

Figure 5. Half Coil (Main Coil) quench development following SC+ Lead quench.

CONCLUSIONS

We completed a systematic study of quench development in the superconducting strands that connect the HINS CH section focusing solenoid coils to the power leads in a prototype cryostat lens. Quenches were induced by turning the copper lead cooling flow to zero. Below 85 A the strand voltage is stable at 6 mV and quenches do not propagate to the coil. At higher currents, the voltage grows slowly and the quenches reach the coil where they develop quickly. We conclude that it is safe to operate the production cryostat lenses (as well as bare solenoids in a liquid helium bath) with only coil voltage detection, without the need for special SC lead voltage taps to protect the superconducting leads.

REFERENCES

[1] I. Terechkine, *et al*., “Focusing Solenoids for the HINS Linac Front End,” LINAC’08, FERMILAB-PUB-405-TD, September 2008.

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[3] C. Hess, *et al.*, “Focusing Solenoid HINS_CH_SOL_01 Test Results,” TD-07-006, FNAL, April 2007.